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Changes in chemical attributes and fractions of organic matter in a Xanthic Ferralsol under different management systems

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ABSTRACT. Examining organic matter fractions is crucial for comprehending variations in soil organic carbon (C) content resulting from the type of management used. The aim of this study was to assess the impact of management systems that utilize both organic and mineral fertilization on soil chemical attributes and organic matter fractions in the Xanthic Ferralsol. This study was conducted in the experimental areas of Embrapa Mandioca and Fruticultura, Cruz das Almas, Bahia State, Brazil. Three cassava and banana production systems, a conventional cassava cultivation system (CAS-CT), an organic banana system (BAN-ORG), and a conventional banana system (BAN-CT), were investigated using the native forest (NF) area as a reference. Soil sampling was conducted within the planting rows at depths of 0.0 - 0.10 and 0.10 - 0.20 m. Macronutrients, soil pH, soil total organic C, particulate organic C, light organic matter, labile-C, mineralizable C, and microbial biomass-C were assessed. BAN-ORG led to an increase in soil pH at both depths. Principal component (PC) analysis showed that organic cultivation was distinguished from the others owing to its strong correlation with soil bases (Ca and Mg), particulate organic C, and labile-C. In the NF and BAN-ORG soils, microbial-C levels in the 0.0 - 0.10 and 0.10 - 0.20 m layers remained consistent, whereas there was a reduction of 30 and 70% for CAS-CT and BAN-CT, respectively, with increasing depth. Mineralizable C (release of CO_2-C) was higher in the NF and BAN-ORG systems than in the conventional system for both evaluated layers. BAN-CT and CAS-CT were strongly correlated with available potassium in PC-2, separating them from BAN-ORG and NF. Management practices implemented in the organic system resulted in an increase in macronutrient levels and a reduction in soil acidity. The elevation of labile-C and particulate organic C in the organic system increased the microbial activity in the soil, particularly in the subsurface layers. Organic management has emerged as a viable approach for enhancing organic C sequestration in the soil and creating favorable conditions for increasing microbial activity in banana cultivation.

Keywords: microbial biomass; labile fractions; components; Ferralsol.

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Introduction

Agricultural production systems that prioritize minimal soil tillage coupled with a substantial input of plant biomass onto the surface, such as organic systems, have been observed to effectively sequester atmospheric CO_2 and enhance its storage within the soil. The augmentation of soil organic matter (SOM) stocks in these systems can markedly improve soil characteristics (Bayer et al., 2002). Conversely, conventional systems exhibit the opposite trend, in which intensive soil tillage creates stressful conditions for soil microorganisms. Reduced SOM input leads to a microbial community reliant on soil organic C, resulting in a pronounced decline in C stocks (D'Andrea et al., 2002).

SOM serves multiple critical functions in ecosystems. In addition to serving as a primary energy source for soil biological activity, it is intricately involved in essential processes such as nutrient cycling, soil aggregation, and water dynamics. Reductions in organic C content can disrupt the soil equilibrium and consequently lead to soil degradation (Roscoe et al., 2006).

Soil organic C can be categorized into labile and stable SOM pools. These pools directly determine the residence time of C in the soil and its impact on soil properties (Bayer et al., 2004). Particular attention has

been paid to the most labile SOM pools, as they exhibit greater sensitivity to short-term management changes, to better understand the potential decrease in organic C content.

Particular focus has been placed on evaluating the particulate organic C, light fraction, microbial C, and oxidizable C fractions to assess the effectiveness of various management practices within diverse agricultural production systems. Numerous studies have suggested that the particulate organic C fraction exerts the most substantial influence on total organic C and demonstrates the highest variability among different management systems (Bayer et al., 2004; Winck et al., 2014). Light organic matter, quantified using the densimetric method proposed by Sohi et al. (2001), contained organic residues at various stages of decomposition. Freixo et al. (2002) concluded that this fraction indicates declining SOM owing to its susceptibility to degradation resulting from soil use and management practices. In addition to its role in SOM degradation and decomposition, the microbial biomass has been extensively used as a biological indicator of soil quality. This is because it represents the most dynamic fraction of SOM and is sensitive to alterations in management practices (Santos et al., 2004; Pessoa et al., 2012; Pragana et al., 2012).

Progress in research on SOM dynamics within agroecosystems holds promise for facilitating the formulation of sustainable management strategies. Unplanned anthropogenic activities are primary contributors to soil degradation. Therefore, understanding the capacity of various soil management systems for C sequestration and storage is crucial.

The hypothesis of this study was that soil management practices in organic cultivation lead to elevated levels of organic C in the soil, with this augmentation being more discernible through the analysis of SOM pools. The objective of this study was to assess the impacts of management systems using both organic and mineral fertilization on the chemical attributes of soil and various SOM pools in a Xanthic Ferralsol.

Material and methods

The study was conducted in the experimental area of Embrapa Mandioca and Fruticultura, in the municipality of Cruz das Almas, Bahia State, Brazil (12°40'0" S and 39°06'0" W, 200 m altitude). The soil was classified as a Xanthic Ferralsol (Souza & Souza, 2001), with a sandy clay loam texture. The climate is tropical, hot, and humid, according to the Köppen classification, with an average annual rainfall of 1,224 mm, relative humidity of 80%, and average annual temperature of 24.5°C.

Three production systems for cassava and banana were selected for this study: conventional cassava cultivation system (CAS-CT), organic banana system (BAN-ORG), and conventional banana systems (BAN-CT). A native forest area (NF) was designated as a reference based on historical patterns of land use and management, as shown in Table 1.

Although the organic cultivation area lacks official certification, managements has diligently adhered to all the production and management protocols stipulated for organic agriculture for over 15 years.

Table 1. History of use and management of the evaluated systems.

Systems	Geographic Coordinates	Description of use and handling
Organic Banana System (BAN-ORG)	12°40'46" S 39°4'34" W	The area under the ORG system has been cultivated with bananas for more than 15 years using fertigation. The process of transition to the organic production system began in 2006. Subsoiling was carried out, 1,000 kg ha^{-1} of gypsum was applied to the soil, and the area was left fallow for three months. A second application of gypsum and limestone was carried out to increase the base saturation to 70%, and the area was left fallow for one year. A new subsoiling was carried out before banana planting, which completed the transition process to the organic system. The first planting was conducted in September 2007. The orchard of the present study was implemented in August 2011. The planting was conducted in double rows at a spacing of 4 × 2 × 2 m when 10 kg of organic compost and 1 kg of natural phosphate were added to the pit. The compost was produced in the area using grass, manure, and castor bean enriched with wood ash as the source of potassium. Fertilization was done every 90 days using 2.5 L of the compost per plant.
Conventional Banana System (BAN-CT)	12°40'0" S 39°06'0" W	The area under CONV management has been cultivated with bananas for more than five years. Before the installation of the orchard, the soil was corrected with limestone. Fertilization with minerals (N and K were applied according to a soil analysis) was done periodically based on the recommendation for the crop. An application of 120 kg ha^{-1} of P and 15 L of manure per pit was used at the start of the experiment. The application of N and K was divided into six events every 60 days, totaling 150 and 300 kg ha^{-1} year of N and K, respectively.
Conventional cassava system	12°39'2" S 39°40'5" W	This area was a pasture for more than 30 years, with a predominance of *Urochloa* spp. The area has been cultivated with cassava under conventional management since 2008. The soil was prepared with

(CAS-CT)		a disc plow, followed by harrowing and mechanized planting. The area was limed in early 2008 and annual fertilizations were applied with NPK according to what the crop needed.
Native forest (NF)	12°39'58" S 39°6'23" W	This is an area (approximately 11.7 ha) of Atlantic Forest ("mata do Cazuzinha"). It is a semideciduous seasonal forest fragment located within an urban area.

Soil sampling was conducted in July 2014 within the planting rows at depths of 0.0 - 0.10 m and 0.10 - 0.20 m. In each study area, three trenches were excavated and regarded as replicates to gather both disturbed and undisturbed soil samples from banana rows. Undisturbed samples were collected from each depth using an Uhland sampler equipped with metallic rings. Disturbed samples were air-dried, disaggregated, and sieved using a 2 mm mesh sieve.

Soil pH was determined in water at a soil:water ratio of 1:2.5. The available P and K contents were extracted using the Mehlich method, P was analyzed using colorimetry, and K was analyzed using flame photometry. H + Al was extracted with a buffered solution of 1 mol L^{-1} calcium acetate at pH 7.0, and Ca, Mg, and Al were extracted with 1 mol L^{-1} KCl and analyzed using atomic absorption spectrophotometry. The cation exchange capacity (CEC), sum of bases (SB), and percentage of base saturation (V%) of the soil were calculated using the potential acidity and exchangeable bases according to the methodologies described by Embrapa Solos (2011).

The soil samples were ground with a mortar, and C was quantified using wet oxidation with 0.167 mol L^{-1} $K_2Cr_2O_7$ in a sulfuric medium to determine the total organic carbon (TOC). The heat released by H_2SO_4, together with an external heating source, was used as the energy source. After oxidation, the excess dichromate was titrated with a 0.5 mol L^{-1} $Fe(NH_4)2(SO_4)2.6H_2O$ solution (Yeomans & Bremner, 1988). Soil TOC stocks were calculated as follows: Est C (Mg ha^{-1}) = [TOC] × Ds × E, where [TOC] is the concentration of TOC in dag kg^{-1}, Ds is the soil density in g cm^{-3}, and E is the thickness of the evaluated layer in cm.

Physical fractionation to obtain particulate organic C (POC) was performed according to a method adapted from Cambardella and Elliot (1992). Mineral-associated organic C (mAOC) content, representing the most stable organic C fraction of the soil, was calculated by subtracting the particulate organic carbon (POC) content from the TOC. The free light organic matter fraction (LF) fraction was determined using the densimetric method using sodium iodide (NaI), according to the procedures described by Sohi et al. (2001). The C content of the LF was determined using dry combustion with an elemental analyzer (TOC Vario Cube, Germany).

Labile soil organic C (lab-C) was extracted from the soil using acid hydrolysis according to a method adapted from Silveira et al. (2008). First, 0.8 g of dried soil (< 2 mm) was added to 50 mL centrifuge tubes, and then 40 mL of 6 mol L-1 HCl was added to obtain a 1:50 soil-to-extractant ratio. The tubes were then heated by immersion in a water bath at 105°C for 2h. Subsequently, the residue was separated from the supernatant by centrifugation for 20 min. at 3,500 rpm. Excess HCl in the residue was removed by washing three times with deionized water and shaking for 10 min. on a horizontal shaker, followed by centrifugation at 3,500 rpm. The residue was oven dried at 60°C, weighed, and quantified using wet oxidation with 0.167 mol L^{-1} of $K_2Cr_2O_7$ solution, according to Yeomans and Bremner (1988). The original method proposed the quantification of C in the supernatant as the C-lab fraction; however, in this study, C in the residue was quantified. Therefore, lab-C was obtained from the difference between the C residue and TOC content.

Microbial activity was determined by quantifying the mineralizable C (respirometry) by means of the release of CO_2 ($C\text{-}CO_2$) captured in 0.5 mol L^{-1} NaOH solution, according to the method proposed by Anderson (1982).

Soil respirometry measurements were obtained from samples collected at depths of 0.0 - 0.10 m and 0.10 - 0.20 m. Upon collection, the samples were stored at 4°C. Before analysis, the samples were removed from refrigeration and equilibrated to room temperature for 24 hours. Subsequently, they were dewormed, passed through a 4 mm mesh sieve, and homogenized. Prior to the respirometry test, the samples were incubated at room temperature for 7 days to restore and balance the microbial activity. Following the incubation period, a respirometry test was initiated using a static method in a laboratory setting. For this, 100 g soil samples were conditioned in hermetically sealed 500 cm^3 plastic bottles containing 30 mL of 0.5 mol L^{-1} NaOH to capture the CO_2 released from the soil. A $C\text{-}CO_2$ evolution curve was obtained by titration 3, 6, 10, 13, 17, 21, 27, and 33 days after incubation. Between the intervals, the samples remained in a controlled environment using a biochemical oxygen demand (BOD) chamber adjusted to 25 ± 1°C. The release of the detached $C\text{-}CO_2$ was performed using a 10 mL aliquot of NaOH in the presence of 0.05 mol L^{-1} $BaCl_2$ titrated with 0.25 mol L^{-1} HCl. After each reading, the vials containing NaOH for $C\text{-}CO_2$ capture were replaced.

The respiration rate per unit biomass, or metabolic quotient (qCO_2), was obtained from the relationship between the basal respiration rate, which consists of the daily measurement of CO_2 production resulting from soil metabolic activity, and microbial biomass (Anderson & Domsch, 1985). The qCO_2 was calculated using the following equation:

$$qCO_2(mgC - CO_2\ g^{-1}\ Cmic.h^{-1}) = RBS\ \frac{(mgC - CO_2\ kg^{-1}\ solo.h^{-1}}{Cmic\ (mgC.kg^{-1}\ solo).10^{-3}}$$

where: qCO_2 is the soil metabolic quotient, RBS is the soil basal respiration, and Cmic is the soil microbial biomass carbon.

The microbial C (Cmic) of the soil was determined using the irradiation-extraction method and a Panasonic microwave oven (900 W power and frequency of 2,450 MHz) according to the methods described by Islam and Weil (1998) and Ferreira et al. (1999). The extractor used was 0.5 mol L^{-1} K_2SO_4. The C content in the extracts of the irradiated and non-irradiated samples was determined using oxidation with 0.066 mol L^{-1} $K_2Cr_2O_7$ in the presence of sulfuric acid without external heating using a solution of 0.033 mol L^{-1} $Fe(NH_4)_2(SO_4)_2.6H_2O$ (Yeomans & Bremner, 1988). The factor (Kc) used to convert the flow from C to C of the microbial biomass was 0.33 (Sparling & West, 1988).

The dataset underwent principal component analysis (PCA) (Sena et al., 2002; Savegnago et al., 2011) to differentiate between agricultural systems. The analyses were made with the FactoMineR statistical package (Lê et al., 2008) in the program R version 3.3.3.

Results and discussion

The principal component analysis (PCA) facilitated the examination of similarities and differences among the studied systems based on chemical and biological variables (Figure 1). All variables under investigation were collectively analyzed to delineate the profiles of each system, enabling the identification of discriminant variables that distinguish one system from another.

The first two principal components (PC) explained 82% and 77% of the total variance at depths of 0.0 - 0.10 m and 0.10 - 0.20 m, respectively.

Soil respiration data showed a higher release of CO_2-C in the NF and BAN-ORG systems than in conventional tillage for both evaluated layers, indicating that these systems promote greater microbial activity in the soil. However, it is important to note that microbial respiration alone does not comprehensively analyze microbial efficiency in substrate utilization (Anderson & Domsch, 1985).

Our findings suggest that organic banana production systems stimulate heightened soil microbial activity, extending beyond the surface to 0.10 - 0.20 m. This will lead to improved (re)cycling of nutrients, consequently benefiting banana productivity. Conversely, the diminished microbial activity observed in conventional tillage systems underscores the necessity of organic fertilization as an indispensable agricultural practice for sustaining soil life.

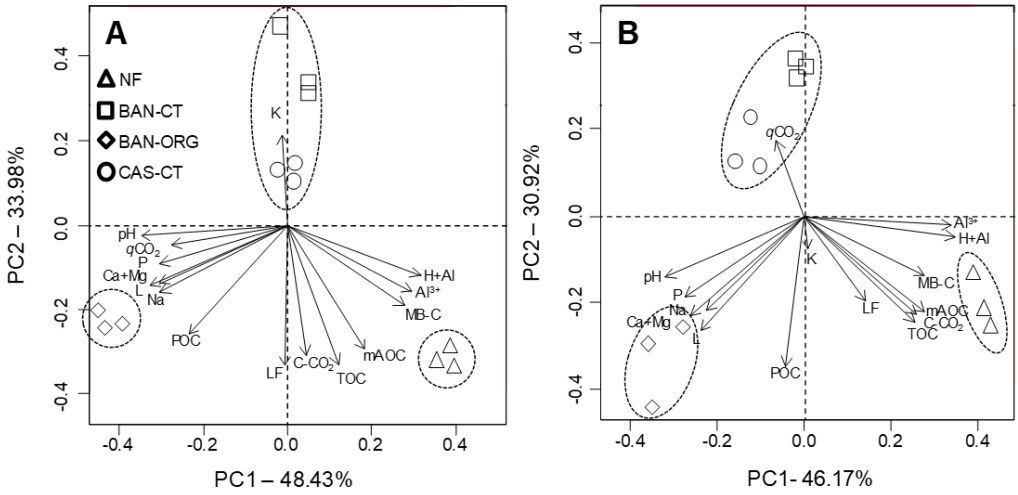

Figure 1. Biplot of the principal components PC1 and PC2 of the principal components analysis for all chemical variables of a Xanthic Ferralsol at 0.0 - 0.10 m (A) and 0.10 - 0.20 m (B) depths under different use and management. NF: native forest; CAS-CT: Conventional cassava system; BAN-CT: Conventional Banana System; BAN-ORG: Organic Banana System. pH: pH in water; P: Phosphorus; K: potassium; Ca + Mg: calcium + magnesium; Na^+: sodium; Al^{3+}: exchangeable acidity; H + Al: potential acidity; TOC: soil total organic C; MB-C: microbial biomass C; CO_2-C: soil basal respiration; qCO_2: metabolic quotient; LF: amount of extracted soil light fraction (C content not measured); POC: particulate organic C; mAOC: mineral associated organic C; L: lability of soil organic carbon calculated as POC/mAOC.

The POC values ranged from 0.3 to 2.7 g kg^{-1} across the soil profile (Table 2) and exhibited a decline with increasing depth, attributed to the heightened accumulation of organic material at the surface. Notably, the BAN-ORG system demonstrated elevated POC values compared with that of the other systems across all evaluated depths (Figure 1), indicating that this management approach enhances the fraction of SOM characterized by high lability, which is crucial for biological activity.

Table 2. Soil organic C contents in different organic matter fractions at 0.0 – 0.10 and 0.10 – 0.20 m depths of Xanthic Ferralsol under different land use and management systems in Bahia State, Brazil.

Systems[1]	TOC	MB-C	CO_2-C	LF	POC	mAOC	L
	(g kg^{-1})	(mg kg^{-1})	(mg CO_2 kg^{-1} soil day^{-1})	(g kg^{-1} soil)	(g C kg^{-1} soil)		
0.0 - 0.10 m							
NF	18.2 ± 0.8	1034 ± 76	26.9 ± 0.9	6.8 ± 0.4	1.4 ± 0.1	16.8 ± 0.8	0.09 ± 0.01
BAN-ORG	14.0 ± 0.4	194 ± 17	22.8 ± 4.1	6.3 ± 0.6	2.7 ± 0.2	11.3 ± 0.6	0.24 ± 0.03
BAN-CT	8.6 ± 1.2	192 ± 20	10.9 ± 0.3	2.3 ± 0.3	0.7 ± 0.0	7.9 ± 1.2	0.09 ± 0.01
CAS-CT	12.3 ± 0.1	500 ± 120	17.4 ± 0.2	2.5 ± 0.1	1.0 ± 0.0	11.3 ± 0.1	0.09 ± 0.00
0.10 - 0.20 m							
NF	22.0 ± 1.6	1014 ± 139	30.2 ± 1.1	4.6 ± 0.2	1.5 ± 0.2	20.5 ± 1.4	0.07 ± 0.01
BAN-ORG	13.1 ± 0.2	203 ± 31	17.4 ± 1.1	4.0 ± 0.7	2.0 ± 0.1	11.1 ± 0.2	0.18 ± 0.01
BAN-CT	8.1 ± 0.8	58 ± 16	10.5 ± 0.4	3.4 ± 0.2	0.3 ± 0.0	7.7 ± 0.7	0.05 ± 0.00
CAS-CT	9.9 ± 0.8	367 ± 83	14.0 ± 0.8	1.3 ± 0.1	0.9 ± 0.1	9.0 ± 0.8	0.10 ± 0.01

[1]NF: native forest; BAN-ORG: Organic Banana System; BAN-CT: Conventional Banana System; CAS-CT: Conventional cassava system. TOC: soil total organic C; MB-C: microbial biomass C; CO_2-C: soil basal respiration; LF: amount of extracted soil light fraction (C content not measured); POC: particulate organic C; mAOC: mineral associated organic C; L: lability of soil organic carbon calculated as POC/mAOC. Mean ± standard error (n = 3).

PC2 showed that potassium (K) was the variable that exerted the greatest influence in distinguishing CT systems from the others at 0.0 - 0.10 m (Figure 1). This suggested that fertilization and nutrient recycling of residues deposited in the soil in the BAN-ORG area may not be sufficient to maintain adequate soil K levels. According to Borges and Oliveira (2000), approximately 5.6 kg of K is exported from the soil for every ton of harvested fruit. The absence of K during the plant cycle can lead to irregular maturation and the production of small, inferior quality fruits (Borges & Oliveira, 2006). The soil should ideally contain a minimum of 0.60 $cmol_c$ dm^{-3} of exchangeable K to achieve the expected productivity of a crop with high-quality fruits (Borges, 2004). Pires et al. (2008) similarly observed low soil K levels in an organic banana production system compared with a conventional system, attributing this to the limited availability of K in organic compounds and fertilizers, thus considering it a constraint of organic systems for crops with high nutrient demands.

The conventional systems were distinguished from the others in PC2 at 0.10 - 0.20 m, primarily due to the values of the metabolic quotient (qCO_2), an index that reflects the rate of basal respiration per unit of microbial biomass. Elevated qCO_2 values suggest increased microbial respiration when organic substrates are used as an energy source, which is indicative of stress (Alves et al., 2011; Pragana et al., 2012).

Overall, the soil chemical quality in the BAN-ORG system was distinguished from that of the conventional systems (Figure 1) primarily because of the elevated levels of calcium (Ca), magnesium (Mg), phosphorus (P), and pH suitable for agricultural production at both studied depths (Table 3). Similarly, Pires et al. (2008) reported levels exceeding the requirements for Ca and Mg in an organic production system compared to a conventional system. In this study, liming was conducted in both systems prior to the experiment, which likely contributed to the elevation of these elements. However, the significant disparity observed between the systems may be attributed to greater absorption or increased losses in conventional systems than in the BAN-ORG system.

Pires et al. (2008) observed that soil pH decreased when mineral fertilizers were used and increased when organic fertilizers were used. The increase in pH values in the BAN-ORG area can be attributed to the accumulation of organic matter in this system, which promoted a reduction in organic anion losses and an increase in the consumption of H^+ released in the rhizosphere in response to the absorption of NH_4^+ or the produced H^+ due by the oxidation of NH_4^+ or R-NH_2 to NO_3^-. The pH increase induced by fertilization resulted in the absence of Al (Al^{3+}) in the soil in the ORG system, which was likely due to the complexation capacity of Al by organic matter. Conversely, soil acidification in conventional systems may be ascribed to the utilization of nitrogen (N) fertilizers, particularly ammoniacal variants, which produce hydrogen ions (H+) through nitrification processes in the soil (Theodoro et al., 2003; Pires et al., 2008).

Table 3. Soil chemical attributes at 0.0 - 0.10 and 0.10 - 0.20 m depths of Xanthic Ferralsol under different land use and management systems in Bahia State, Brazil.

Systems[1]	pH (H_2O)	Mehlich-P (mg dm^{-3})	K	Ca+Mg	Na^+	Al^{3+}	H^+Al^{3+}
			----------(cmol$_c$ dm^{-3})----------				
			0.0 - 0.10 m				
NF	4.6 ± 0.03	6.7 ± 0.3	0.22 ± 0.01	1.51 ± 0.09	0.06 ± 0.01	0.8 ± 0.05	6.6 ± 0.08
BAN-ORG	7.0 ± 0.06	66.7 ± 12.5	0.24 ± 0.01	7.05 ± 0.12	0.43 ± 0.02	0.0 ± 0.00	0.7 ± 0.32
BAN-CT	5.3 ± 0.03	11.3 ± 0.8	0.38 ± 0.01	1.91 ± 0.10	0.07 ± 0.00	0.2 ± 0.00	2.9 ± 0.11
CAS-CT	6.0 ± 0.00	39.7 ± 4.3	0.18 ± 0.03	2.06 ± 0.11	0.02 ± 0.00	0.0 ± 0.00	1.4 ± 0.06
			0.10 - 0.20 m				
NF	4.6 ± 0.10	6.3 ± 0.3	0.19 ± 0.01	1.46 ± 0.15	0.05 ± 0.01	0.8 ± 0.08	6.7 ± 0.32
BAN-ORG	6.7 ± 0.03	49.3 ± 10.2	0.20 ± 0.04	6.24 ± 0.16	0.44 ± 0.02	0.0 ± 0.00	1.4 ± 0.06
BAN-CT	4.9 ± 0.08	3.7 ± 0.6	0.21 ± 0.05	1.62 ± 0.13	0.11 ± 0.01	0.4 ± 0.05	3.4 ± 0.13
CAS-CT	5.9 ± 0.03	31.3 ± 6.0	0.13 ± 0.02	2.15 ± 0.11	0.02 ± 0.00	0.0 ± 0.00	1.5 ± 0.03

[1]NF: native forest; BAN-ORG: Organic Banana System; BAN-CT: Conventional Banana System; CAS-CT: Conventional cassava system. Mean ± standard error (n = 3).

In the BAN-ORG system, the soil exhibited a high available P content, surpassing the requirements of banana plants. As suggested by Borges and Souza (2004), soils with P levels exceeding 30 mg dm^{-3} may not necessitate phosphate fertilization, implying that nutrient cycling within the BAN-ORG system adequately sustains the crop's productivity. Nogueira et al. (2008) observed elevated P concentrations in systems using organic fertilizer.

Conclusion

Management practices implemented in the organic system increased macronutrient levels and reduced soil acidity. In contrast, banana cultivation under the conventional system notably diminished soil nutrient content, except for potassium. Furthermore, the organic system improved the organic C content of the soil, indicating enhanced preservation of organic matter. The elevation of labile-C and POC in the organic system increased the microbial activity in the soil, particularly in the subsurface layers. Notably, POC is a sensitive indicator of changes in SOM levels owing to management practices. These findings suggest that organic management is a promising strategy for enhancing carbon sequestration and fostering beneficial microbial dynamics in banana cultivation.

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